Testing General Relativity and Measuring Black Hole Spin with Constellation-X

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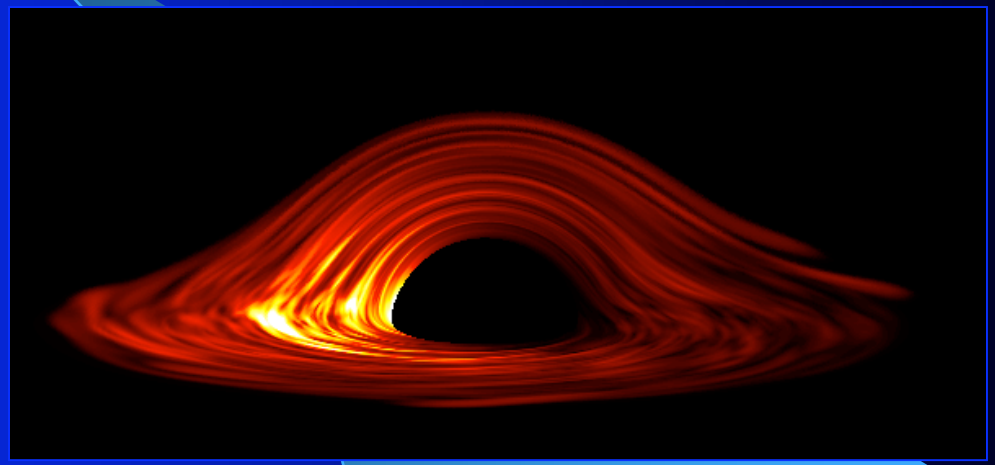


The GR/BH-Spin panel

- Fred Baganoff (MIT)
- Giorgio Matt (Rome)
- James Reeves (Keele, UK)
- Chris Reynolds (Maryland, Chair)
- Kim Weaver (NASA-Goddard)
- Andy Young (Bristol)

Top-level overview
The "Two Questions"

- What are the demographics of black hole spin?
  - How did black holes form/grow?
  - Is spin an important energy source?
- Is General Relativity the correct theory of gravity in the strong-field regime?
  - Is the space-time close to black holes correctly described by the Kerr Metric

Must always remember…

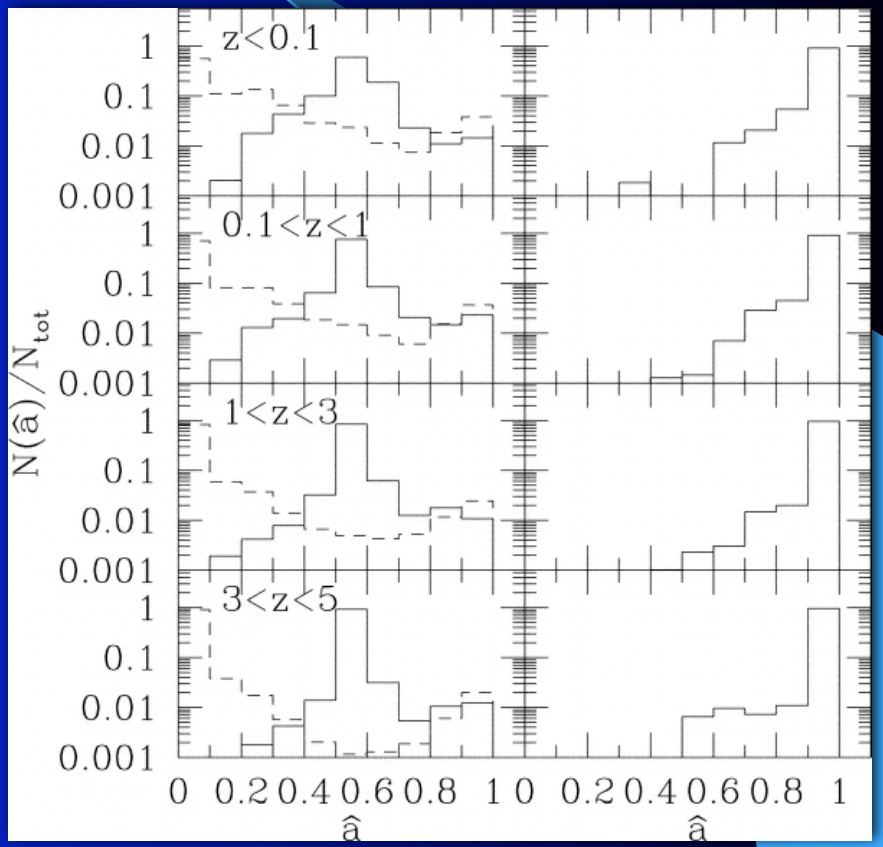
All X-rays from black holes originate, ultimately, from an accretion process.

X-ray signatures of strong gravity need to be understood in the context of the (incomplete) theory of accretion!

We can make this a strength… Con-X can simultaneously explore the astrophysics of accretion as well as strong gravity physics

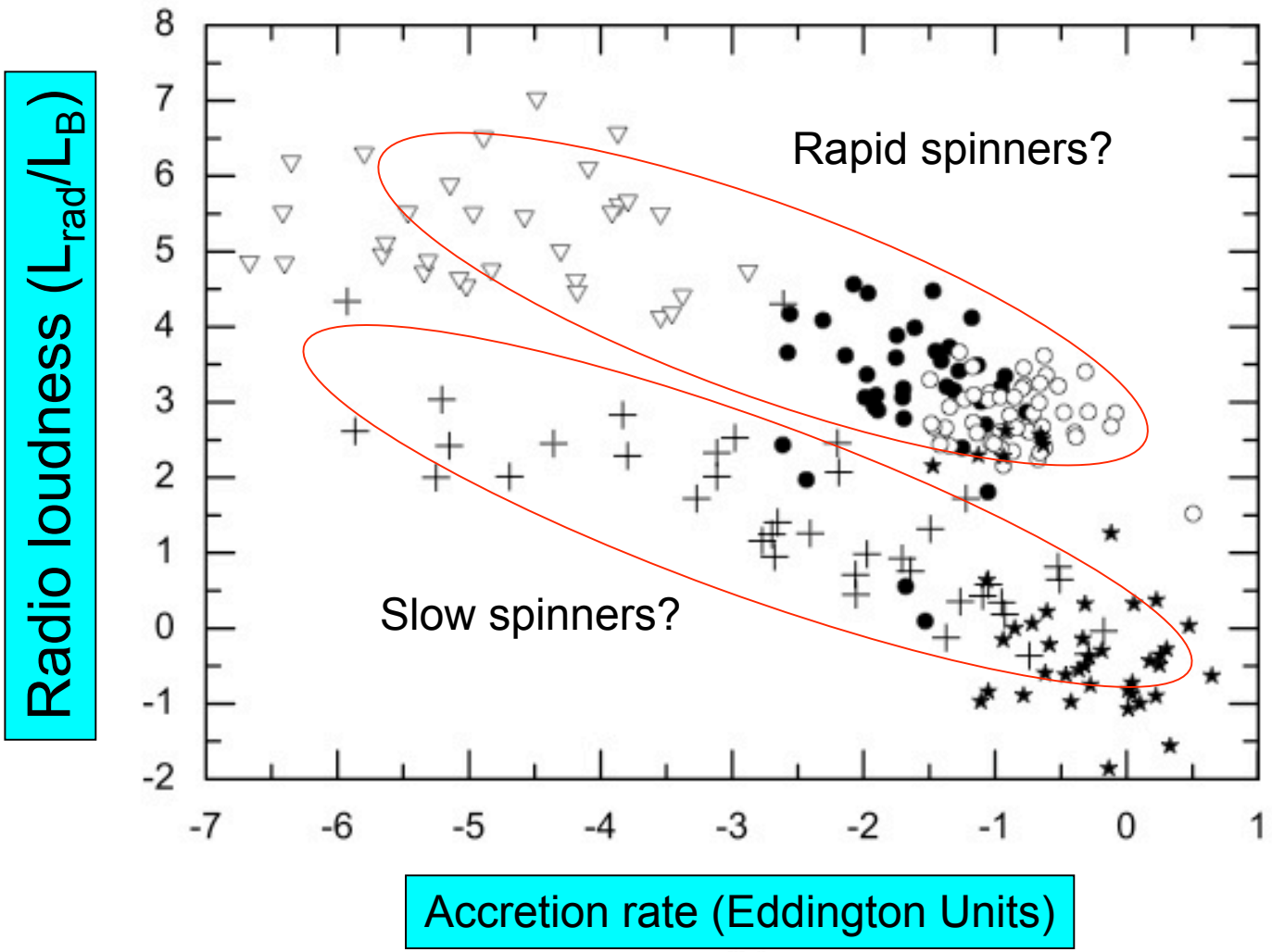
Question 1: What are the demographics of black hole spin?

- **Why do we care?**
- Fossil record of black hole formation/growth
  - Spin of stellar-mass black holes probably unchanged since formation… spin probes formation event
  - Spin of supermassive black hole encodes merger/accretion history
- Spin as an energy source
  - Processes within ergosphere of a Kerr black hole can extract rotational energy
  - Energy source for jets?



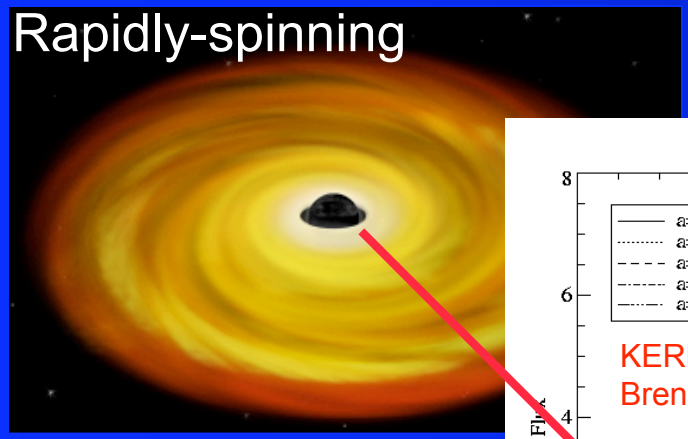
Volonteri et al. (2005)

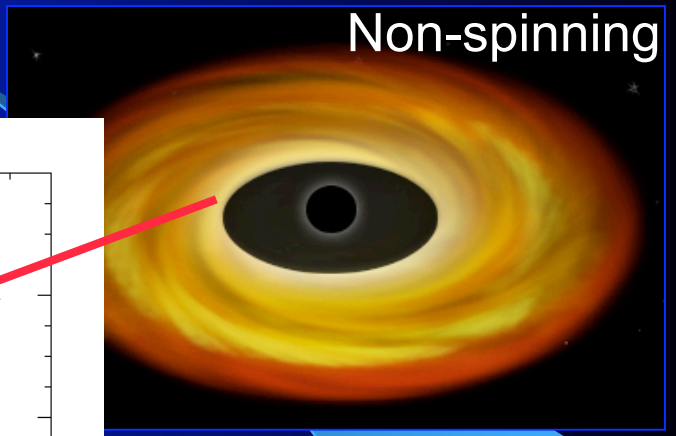
The radio-quiet/radio-loud dichotomy in AGN

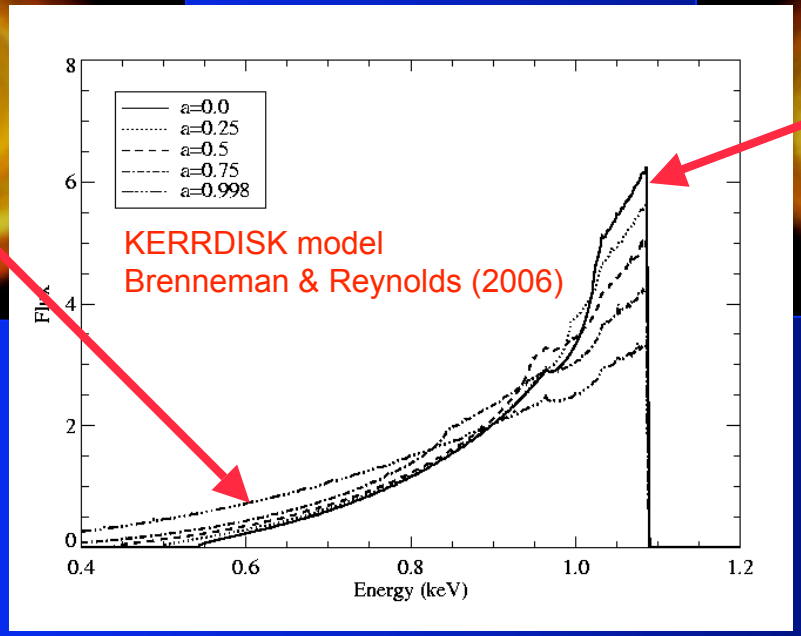


Sikora et al. (2007)

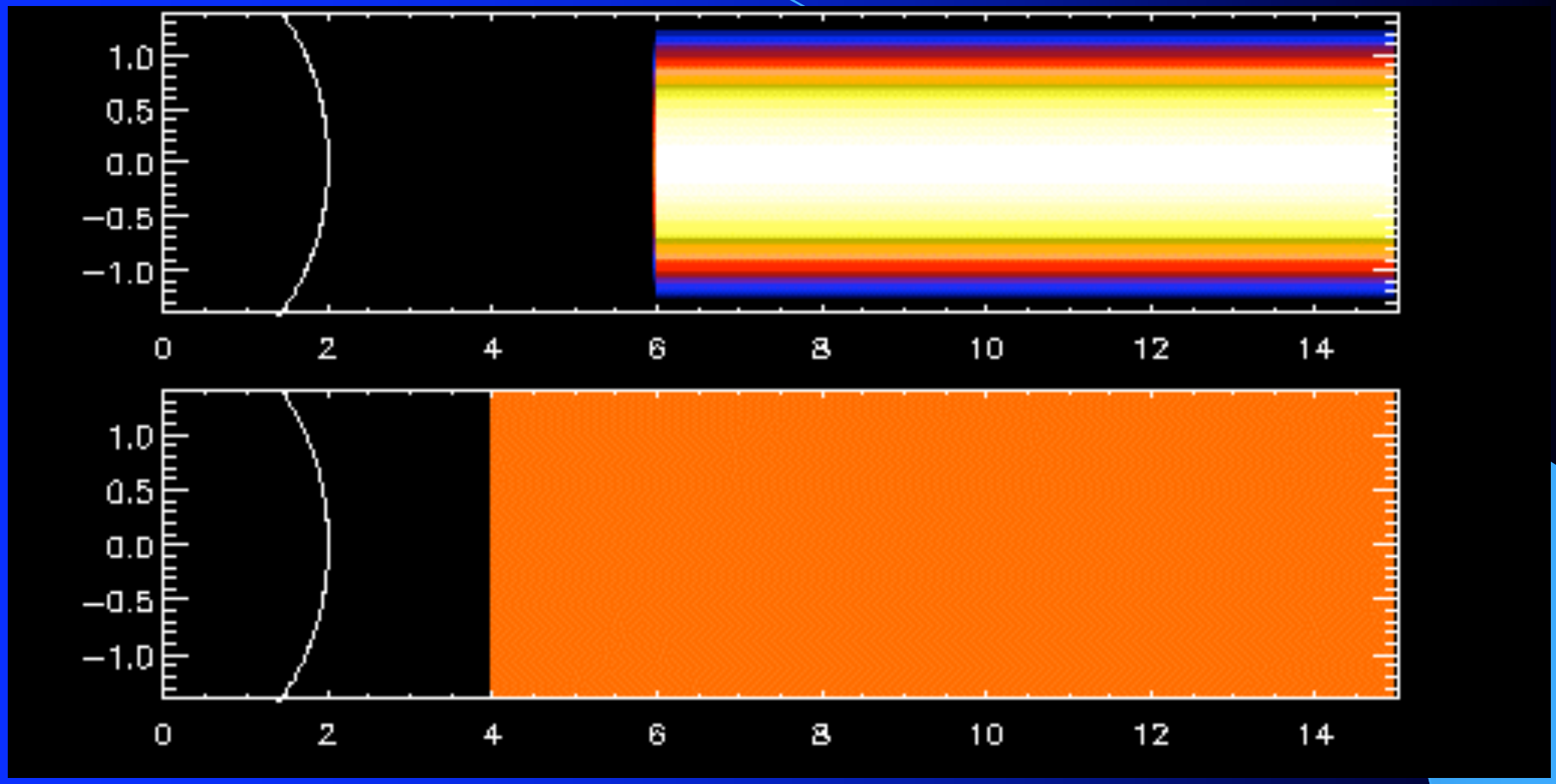
Primary method… measure black hole spin using the width/profile of the broad iron line…



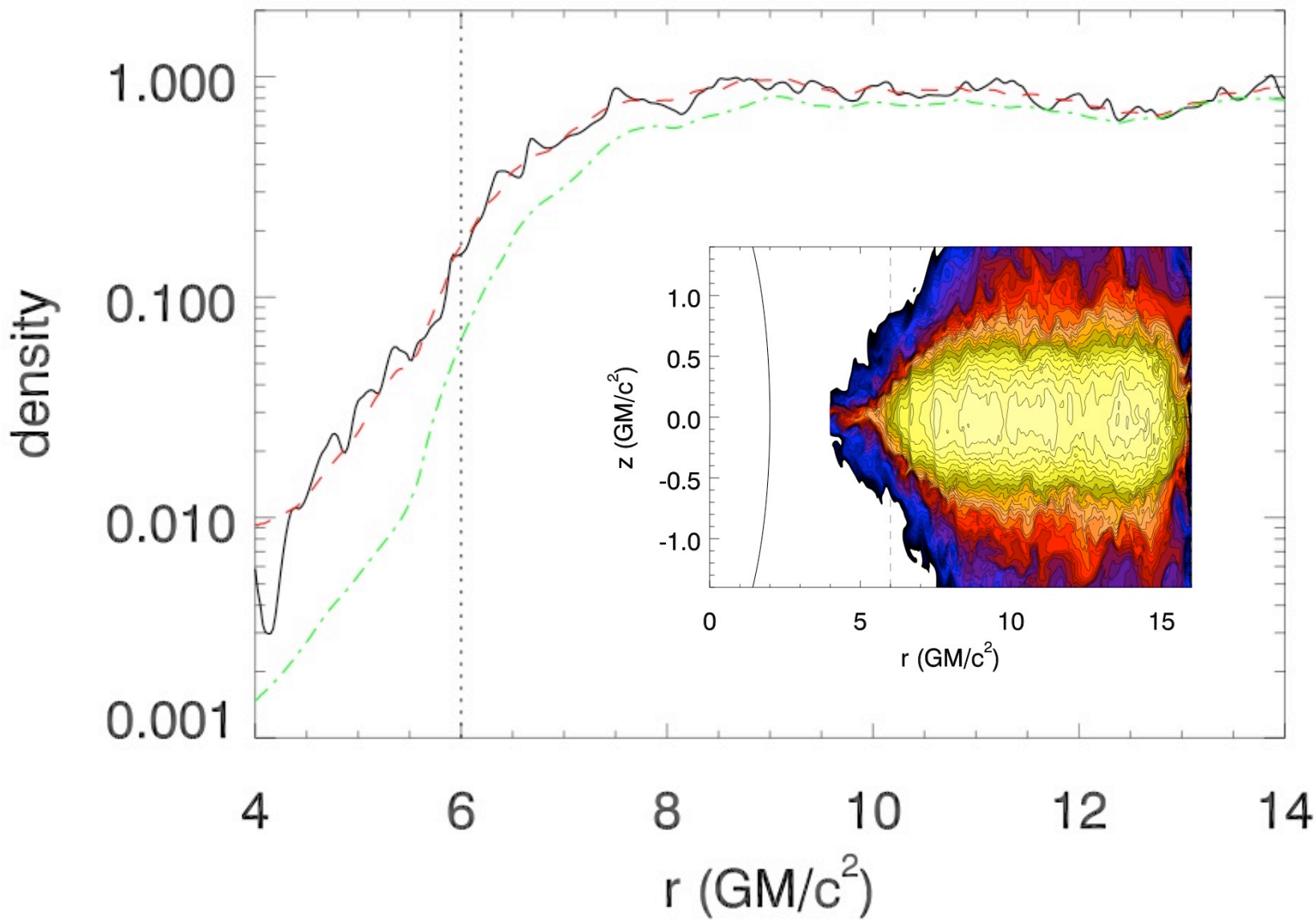




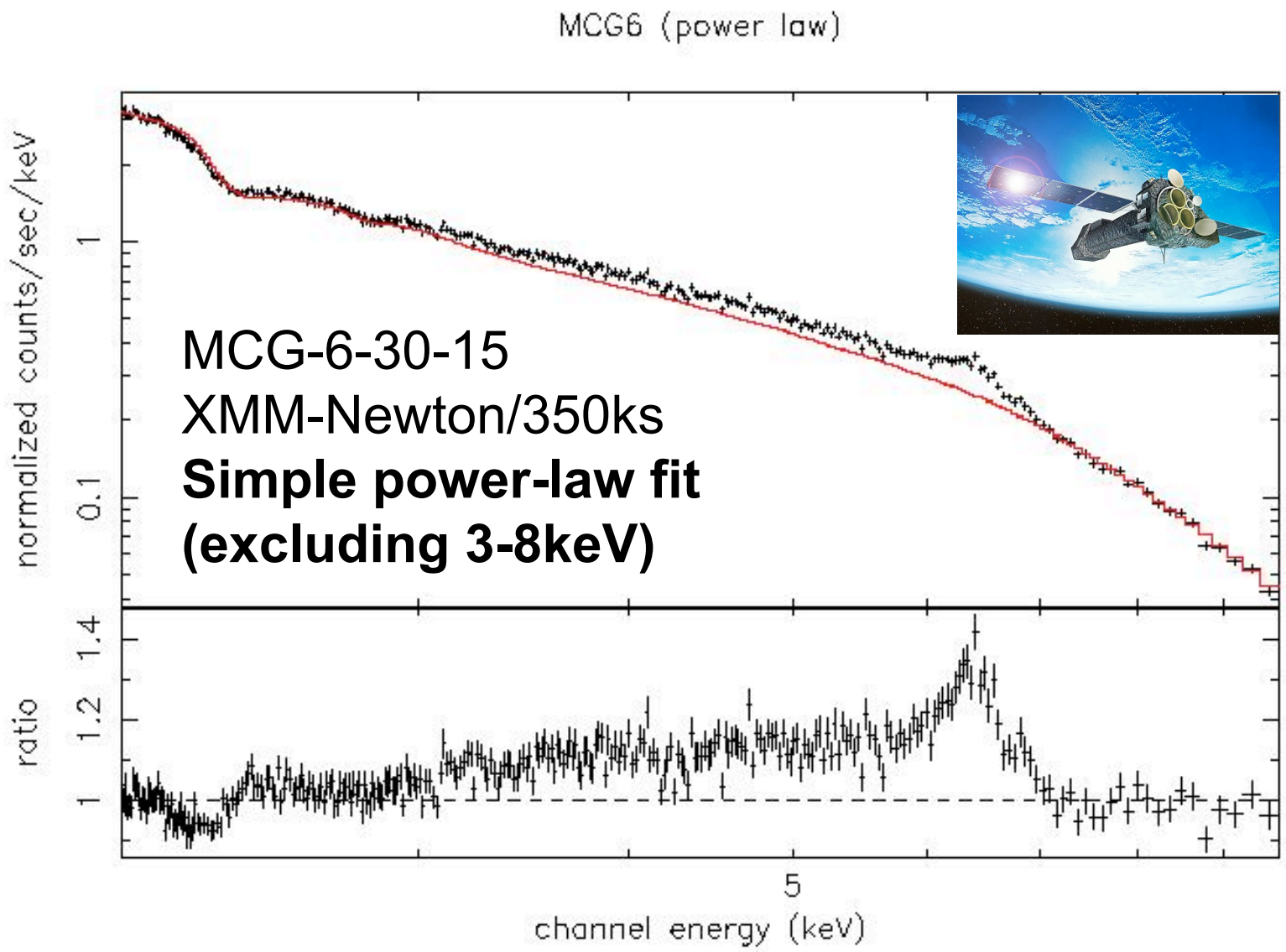
- **Feature :** Spin measurement independent of mass or distance
- **Theoretical assumption** : X-ray reflection / iron line emission truncates at the innermost stable circular orbit (ISCO conjecture).

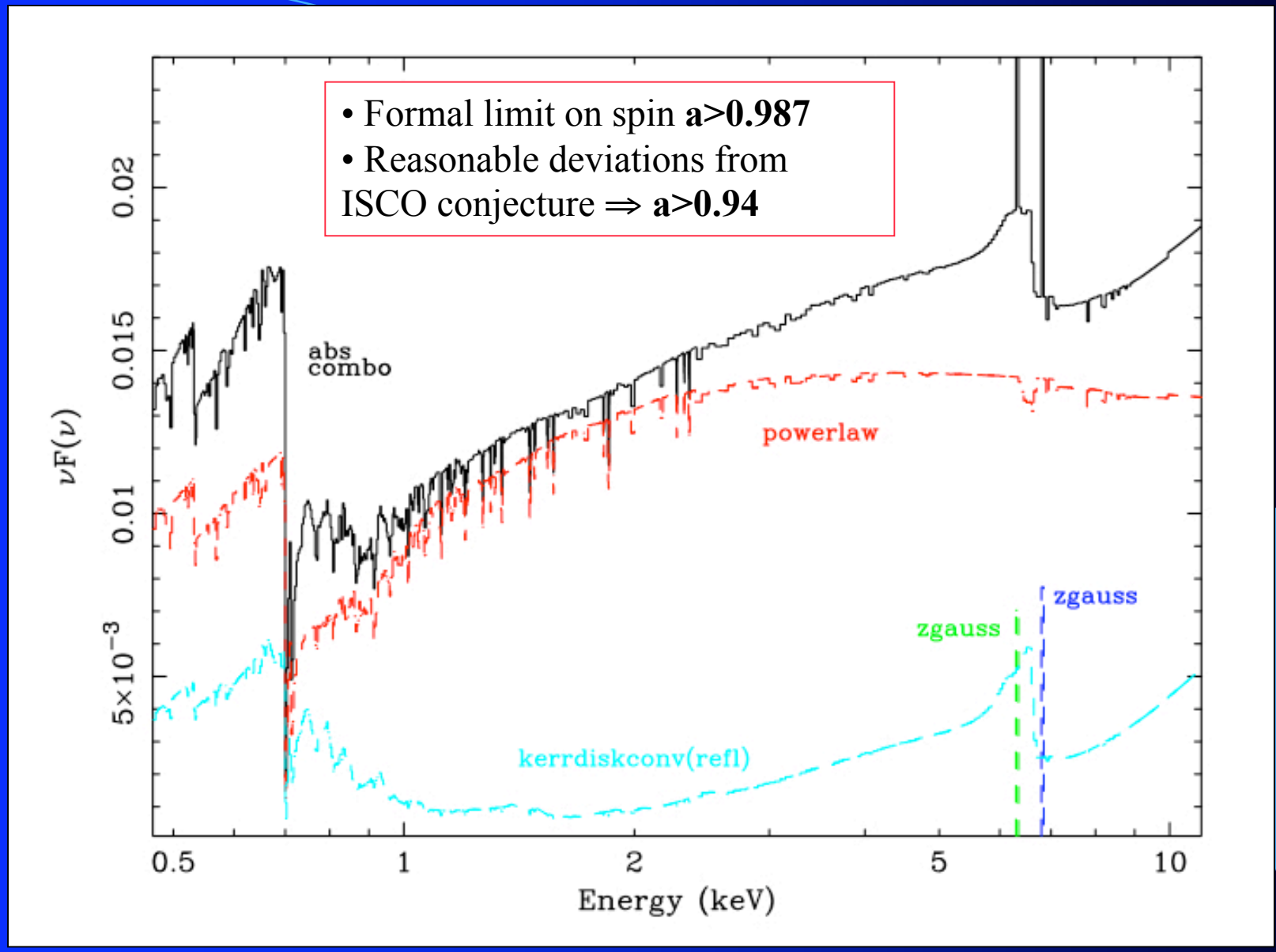


Reynolds & Fabian (2008)



Reynolds & Fabian (2008)


MCG6 (power law)
normalized counts/sec/keV
1
0.1
ratio
1.4
1.2
1
5
channel energy (keV)
MCG-6-30-15
XMM-Newton/350ks
Simple power-law fit
(excluding 3-8keV)

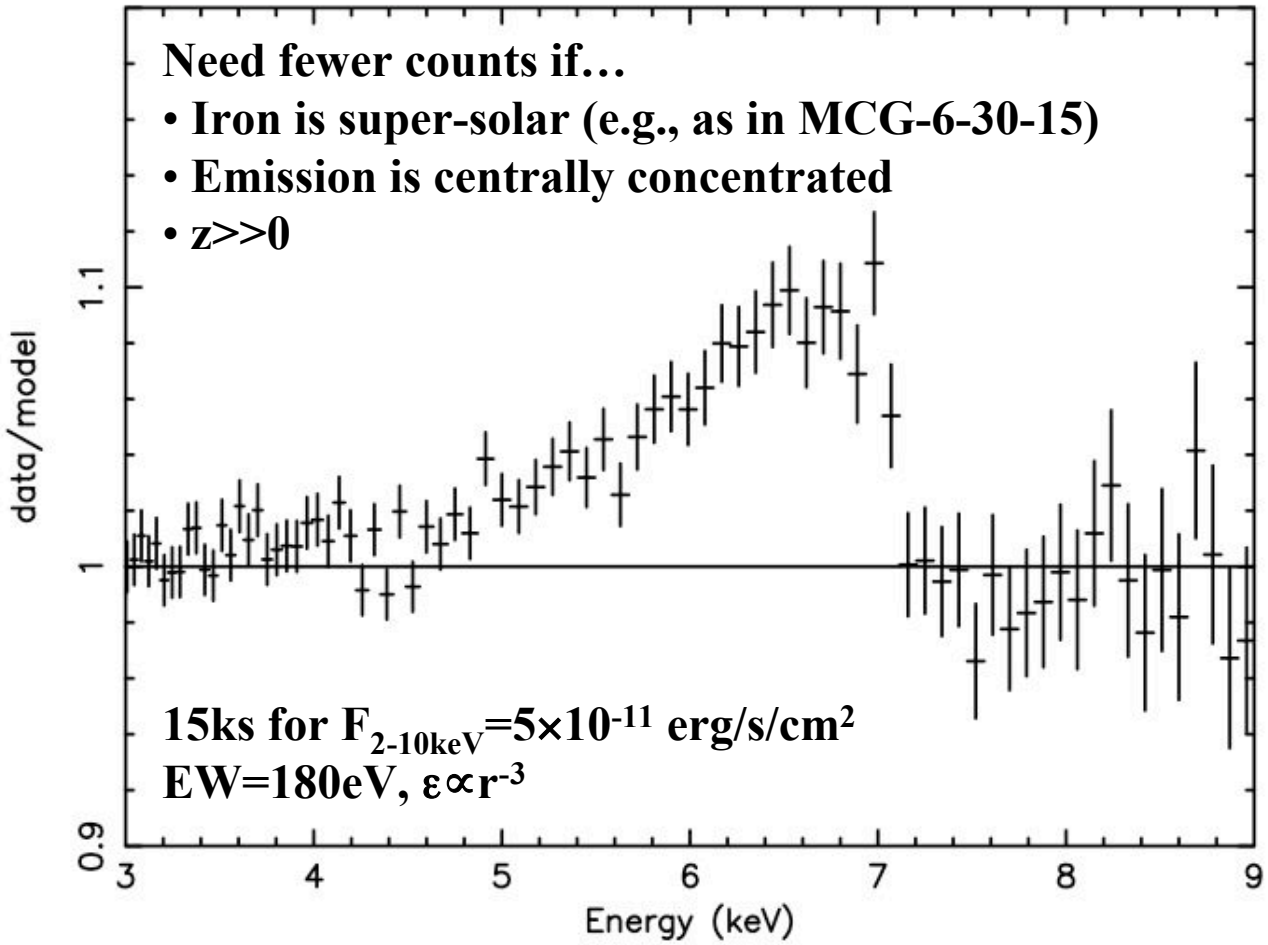


Brenneman & Reynolds (2006)

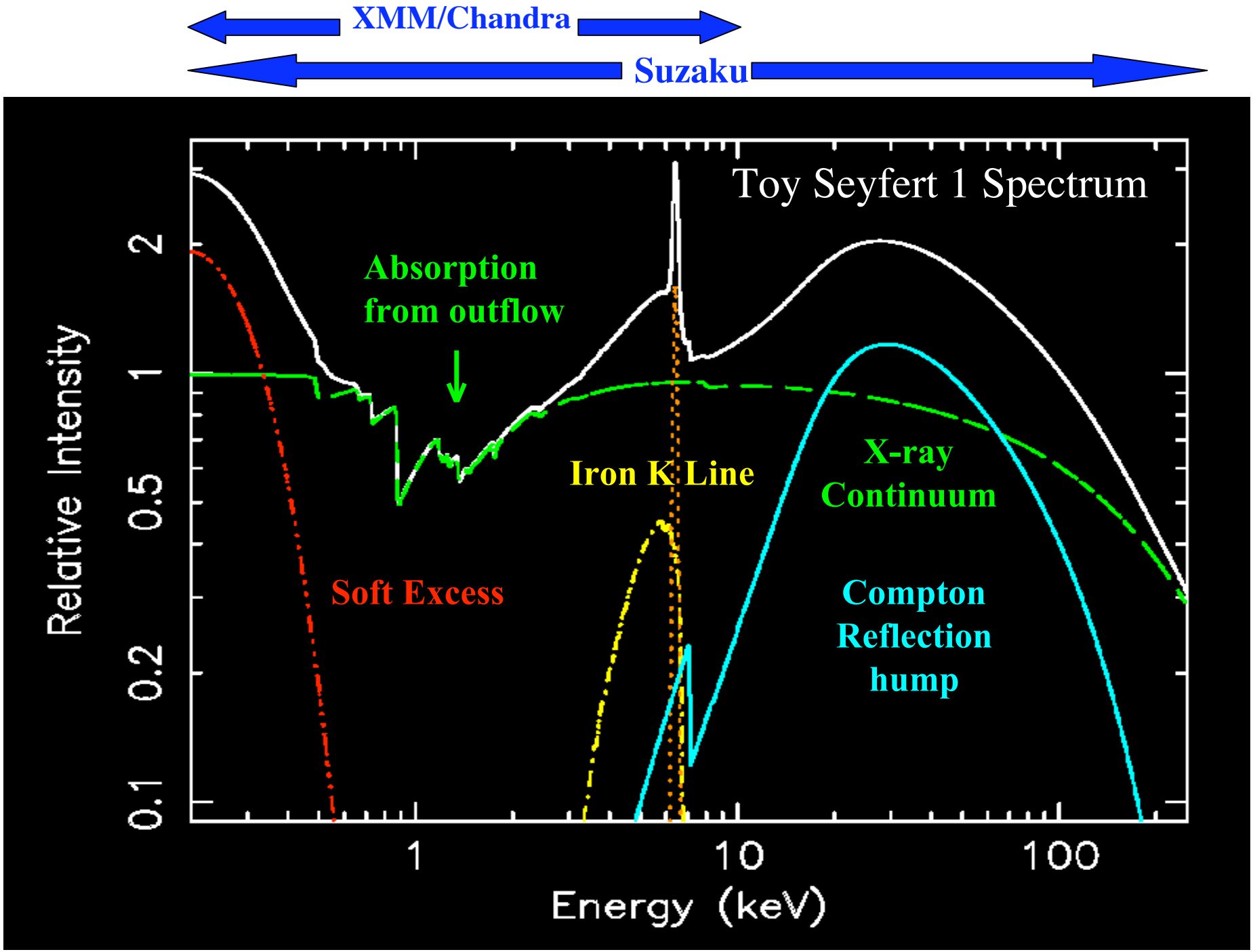
Preliminary : Need to simulate more realistic spectra and include constraints from the hard X-ray telescope

Con-X simulation with 1 million photons in 2-10keV band

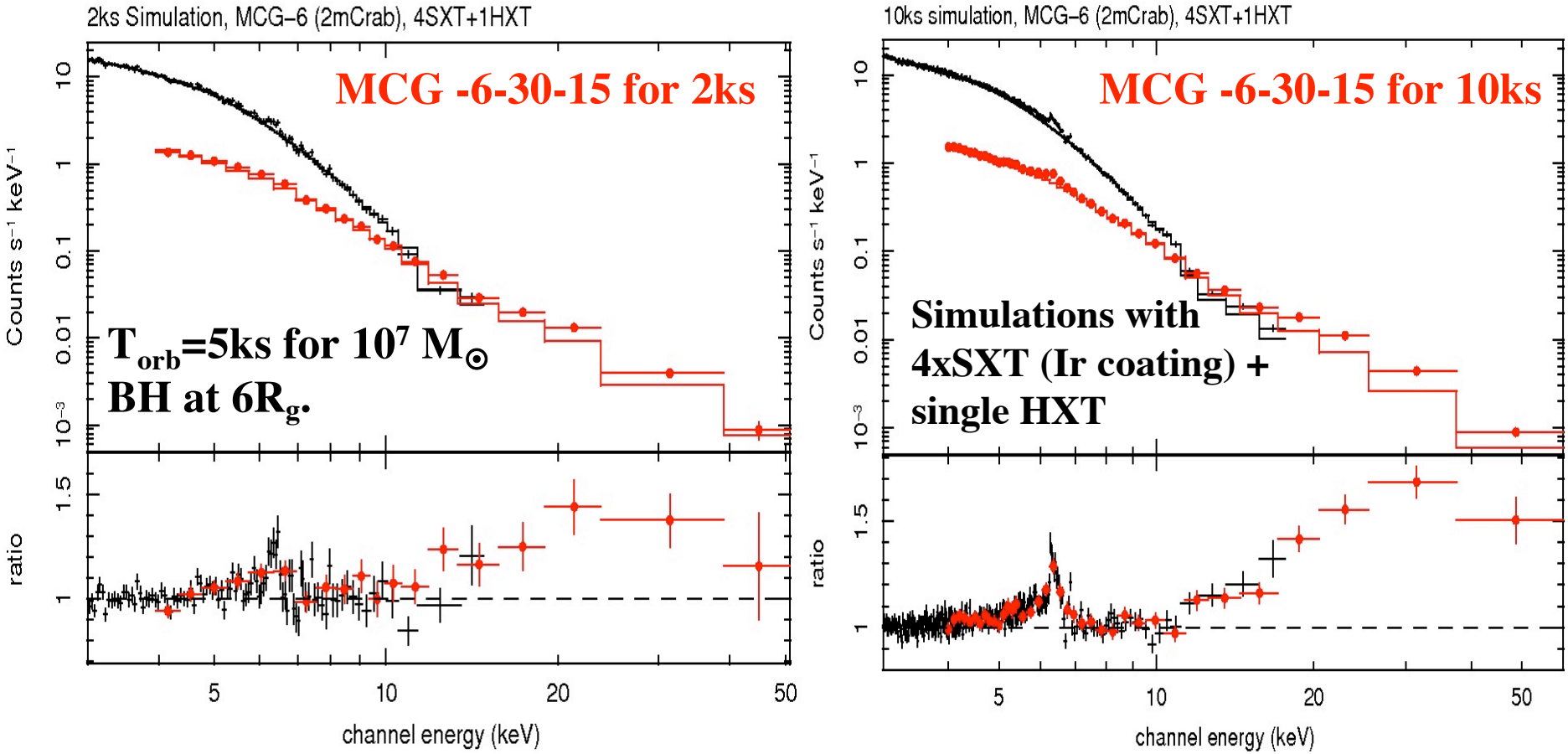
Constrains a>0.90 for a_{model}=0.95



15ks observation for $F_{2-10keV}=5\times10^{-11}$ erg/s/cm²


XMM/Chandra
Suzaku
Toy Seyfert 1 Spectrum
Absorption
from outflow
Iron K Line
X-ray
Continuum
Soft Excess
Compton
Reflection
hump
Relative Intensity
0.1
0.2
0.5
1
2
1
10
100
Energy (keV)

Improving constraints on relativistic Fe K line variability by adding high energy response



Broad line+reflection constraints improved by including a HXE. Even in 2ks, "R" can be constrained to 40% (vs no constraint without HXE) and the iron line parameters to ~30% accuracy (x2 improvement). ***A modest HXE improves the feasibilty of tracking variations in Fe K and reflection on <orbital timescales***.

Observing strategy and sample size…

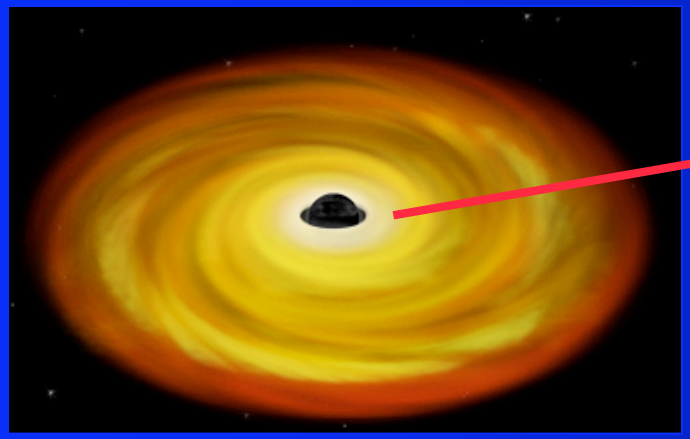
- **Strategy : target known AGN on the basis of flux and the presence of a broad iron line… "run down the log N - log S curve"**
- Using HEAO-A1 LogN-LogS…

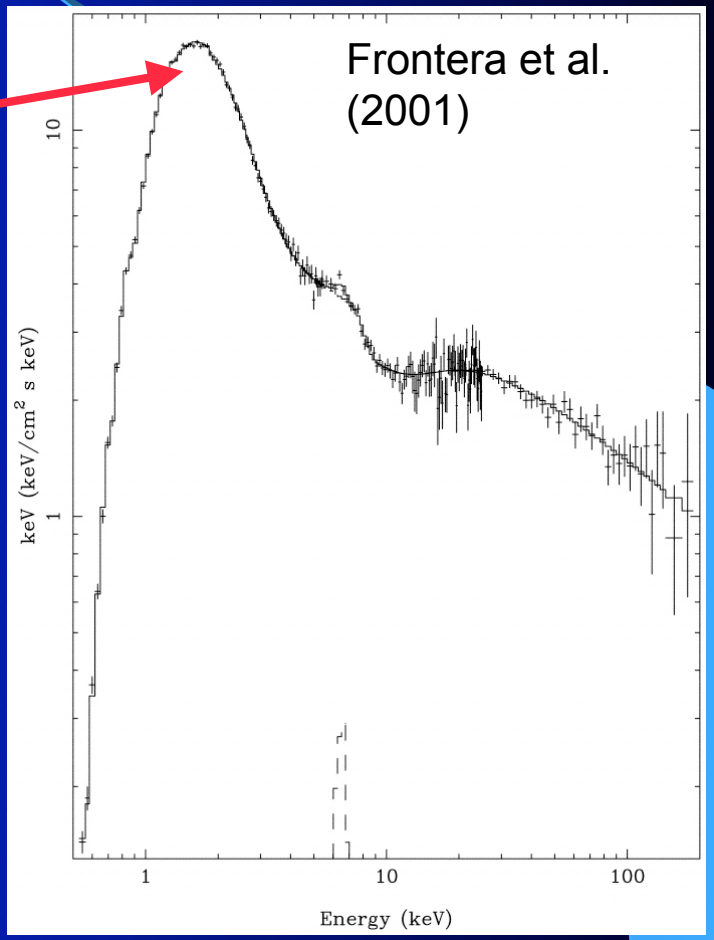
$$N_{tot} \approx 140 \left(\frac{f}{0.5}\right)^{2/5} \left(\frac{n_{ph}}{10^6}\right)^{-3/5} \left(\frac{\Omega}{3\pi}\right) \left(\frac{T}{10^7\, s}\right)^{3/5}$$

  - f is fraction of sources with broad lines
  - n_{ph} is number of 2-10keV photons needed for individual measurement

- Need precusor survey to identify sources with broad iron lines
  - Start with suitable parent sample (e.g. Swift/BAT survey)
  - Snapshot survey of 500 AGN (10Ms total provides sufficient s/n to determine presence of relativistic iron lines)
  - Some fraction of this precusor work will be conducted by XMM and Suzaku beforehand

Secondary method : Black hole spin from thermal accretion disk continuum



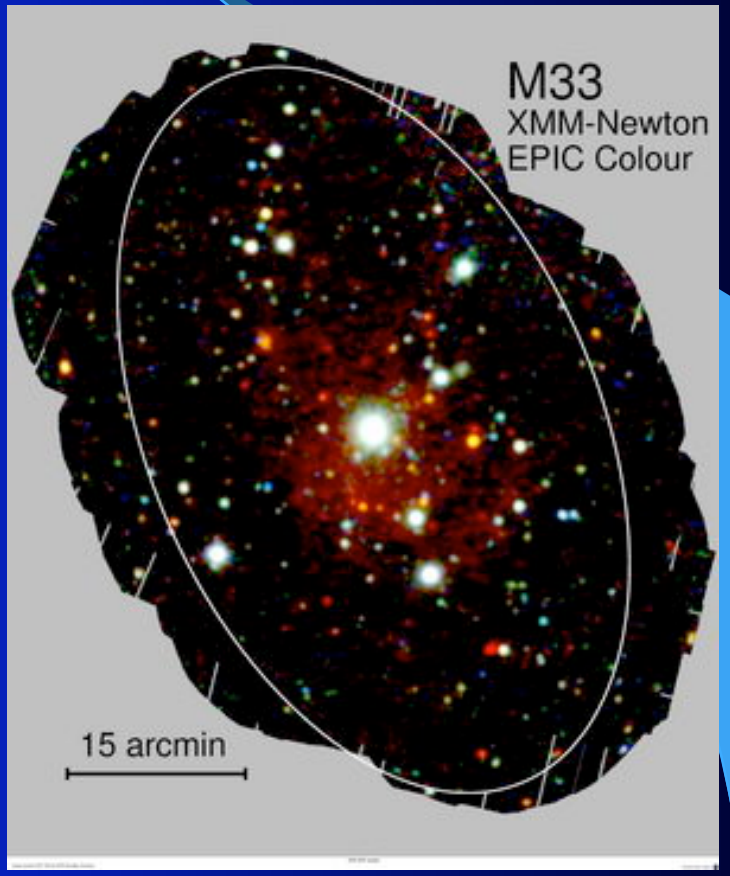


• **Features** : applicable in states when iron line is hard to discern. But need to know mass, distance, inclination independently

• **Theoretical uncertainty** : Precise form of disk spectrum after processing by disk atmosphere. Also relies on ISCO conjecture.

Spins of extragalactic stellar-mass black holes?

- Examine spin as function of environment
- Compared with Galactic sources…
  - Easier to get approx. distances!
  - Absorption less problematic
  - Big-glass needed to get masses and inclinations



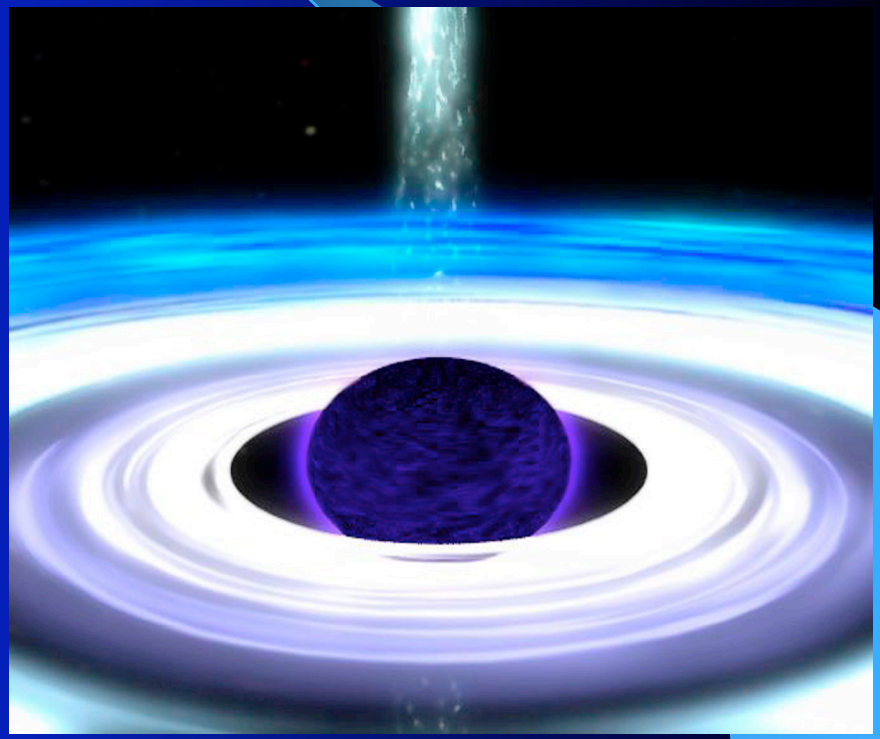
Full spectral imaging simulations needed to assess impact of source confusion (based on Chandra maps)

Question 2 : Is spacetime close to a black hole described by the Kerr metric

- Why do we care?
  - GR is a fundamental pillar of physics; our basis for understanding (macroscopic) structure of space & time
  - BUT… GR is mostly un-tested in strong-field region
  - Note that expected failure points are in extreme regimes (Planck scales around a "spacetime singularity"; or on length scale of any compactified extra dimensions)
- Primary method:
  - Need more information than contained in single iron line profile…
  - Look at **time variability of disk reflection spectrum**

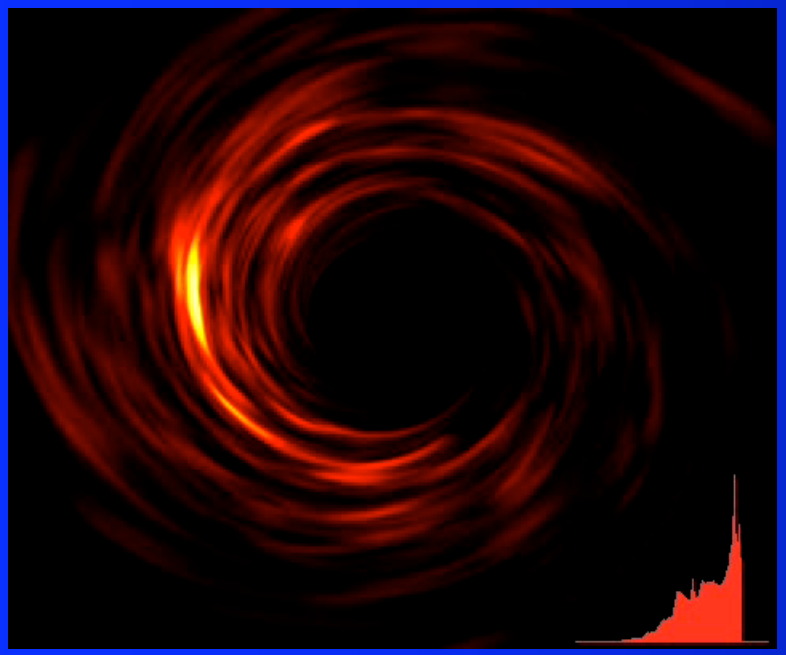
Major theoretical uncertainty : geometry/nature of the X-ray source!

- The (extreme) possibilities…
  - **Base of a jet**
  - **Thick/spherical corona**
  - **Disk-hugging magnetic corona**
  - Expect very different types of iron line variability in these cases

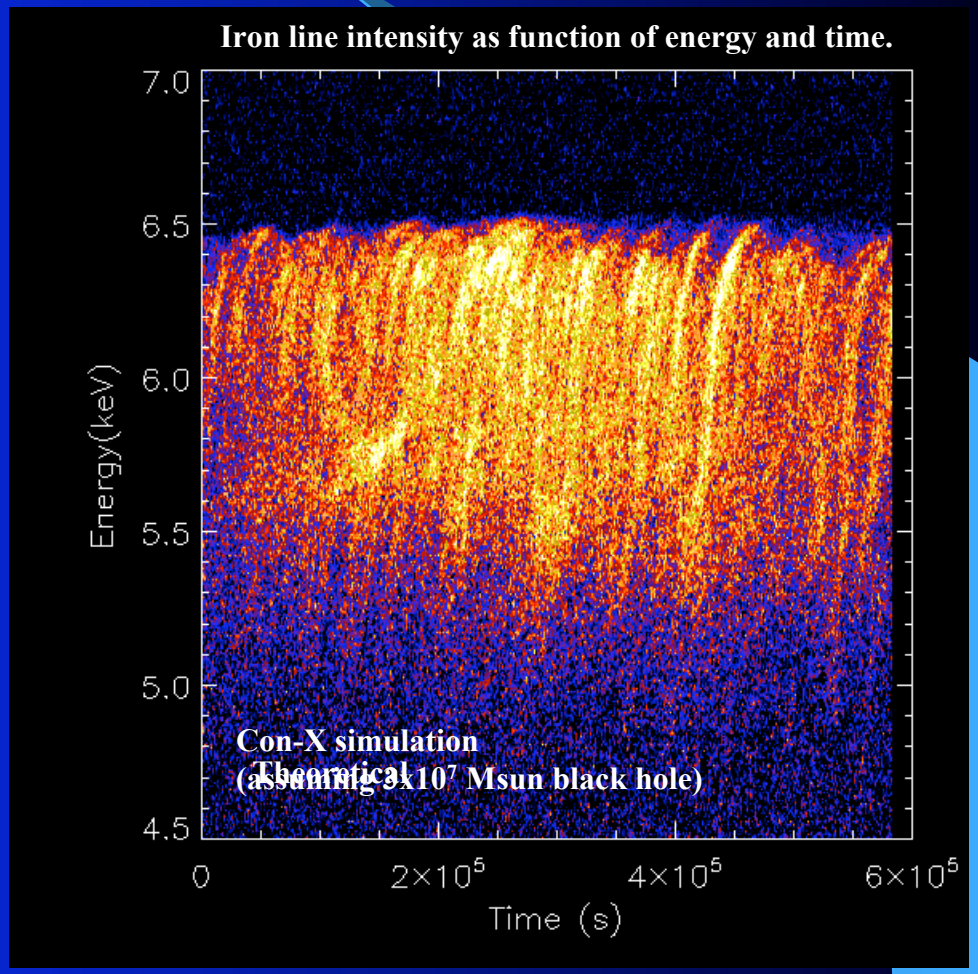


The nature/geometry of the X-ray source is a long-standing problem and will not be solved by our panel… must carry forward all possibilities

Disk hugging corona : orbiting hot spots

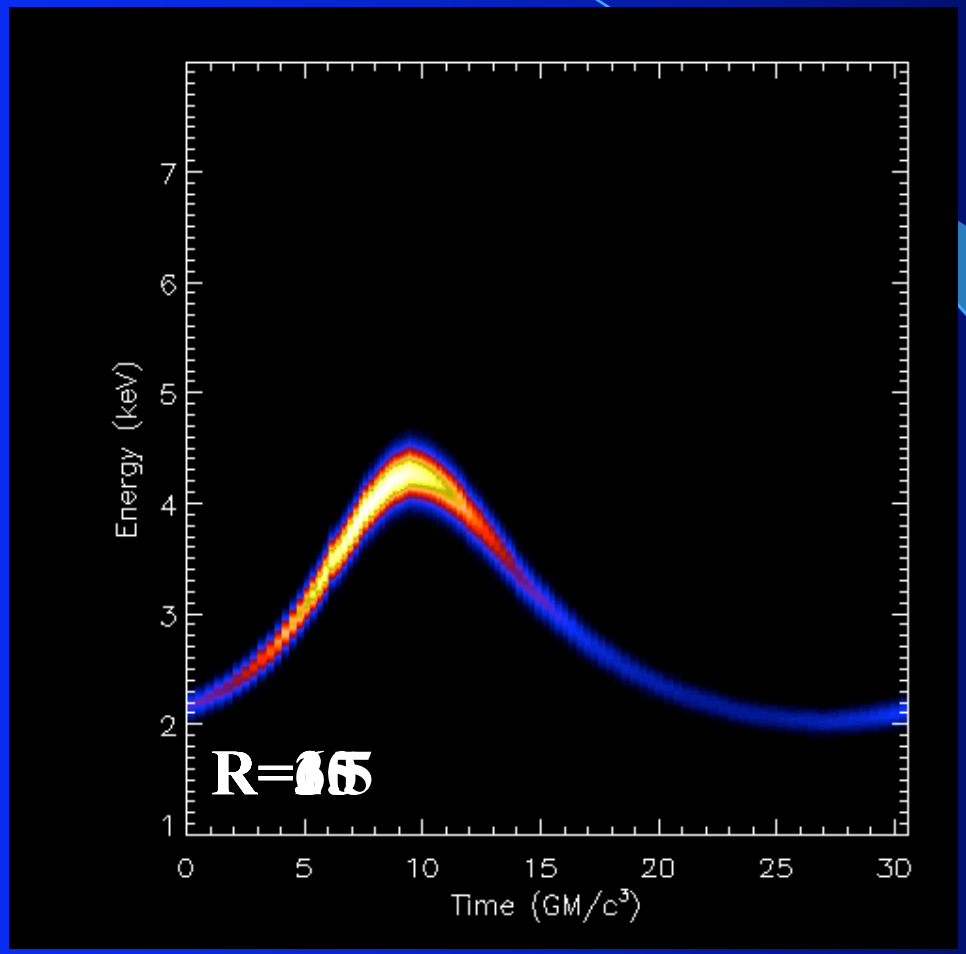


Arcs trace orbits of disk material around black hole… can be compared with predicted GR orbits

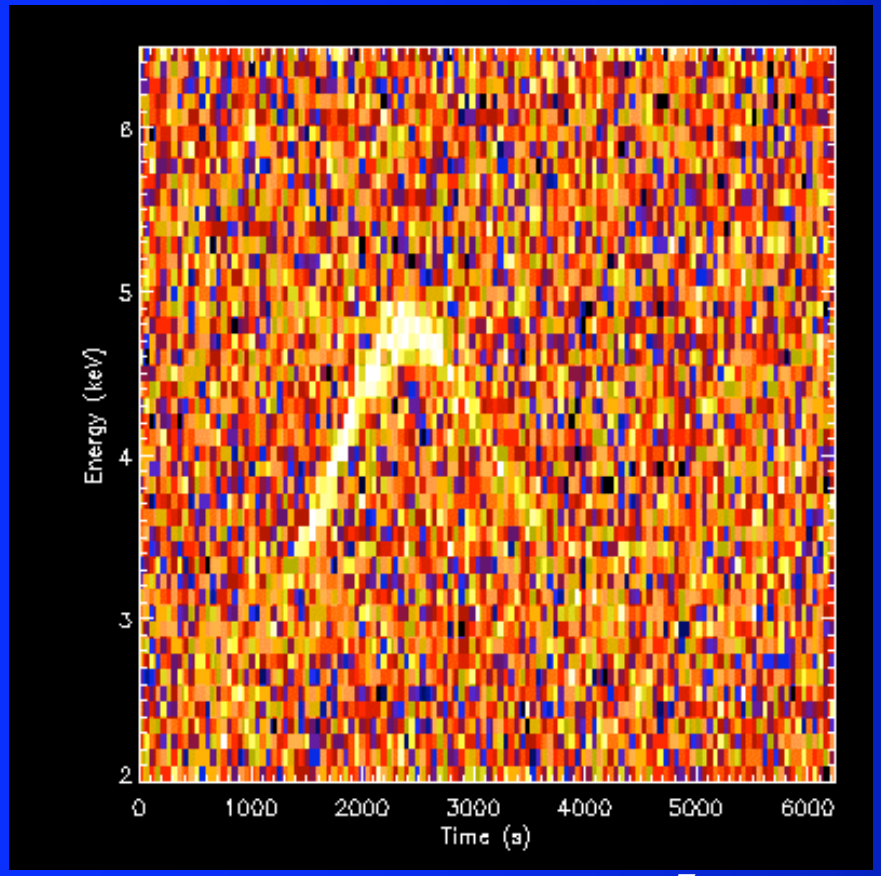


Keplerian orbit of a single “hot spot”

a=0.98
i=30^{o}



A procedure for testing GR…

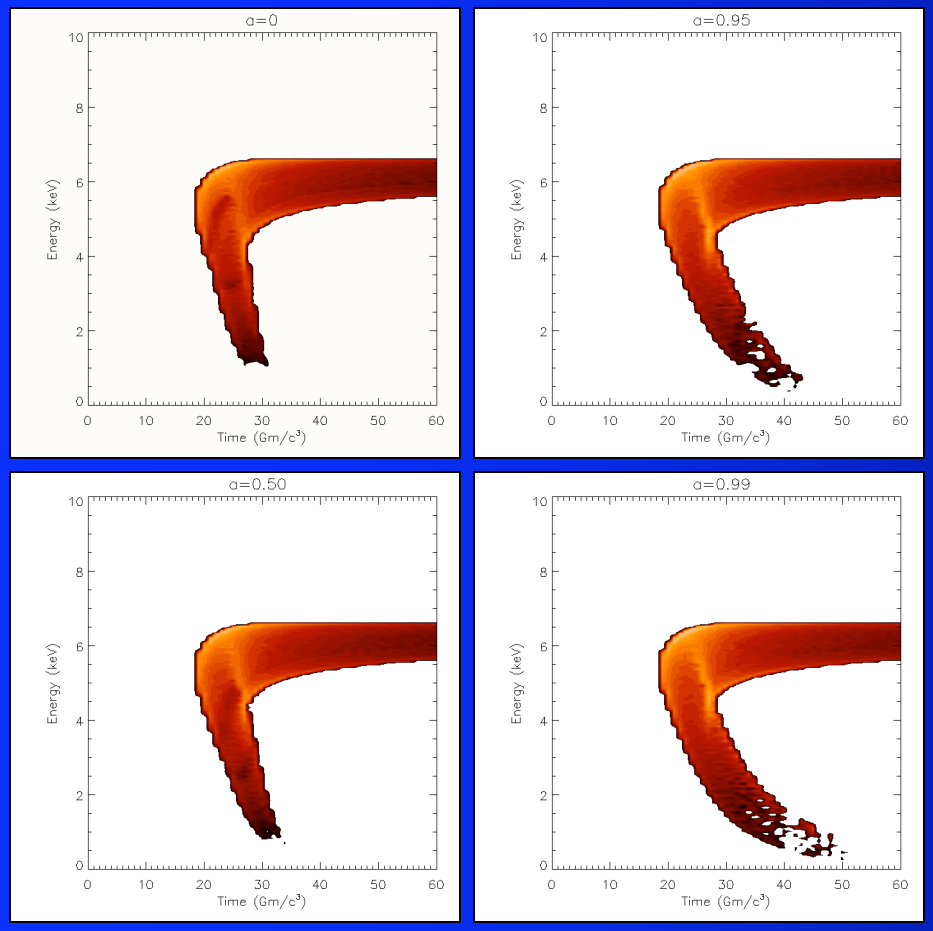


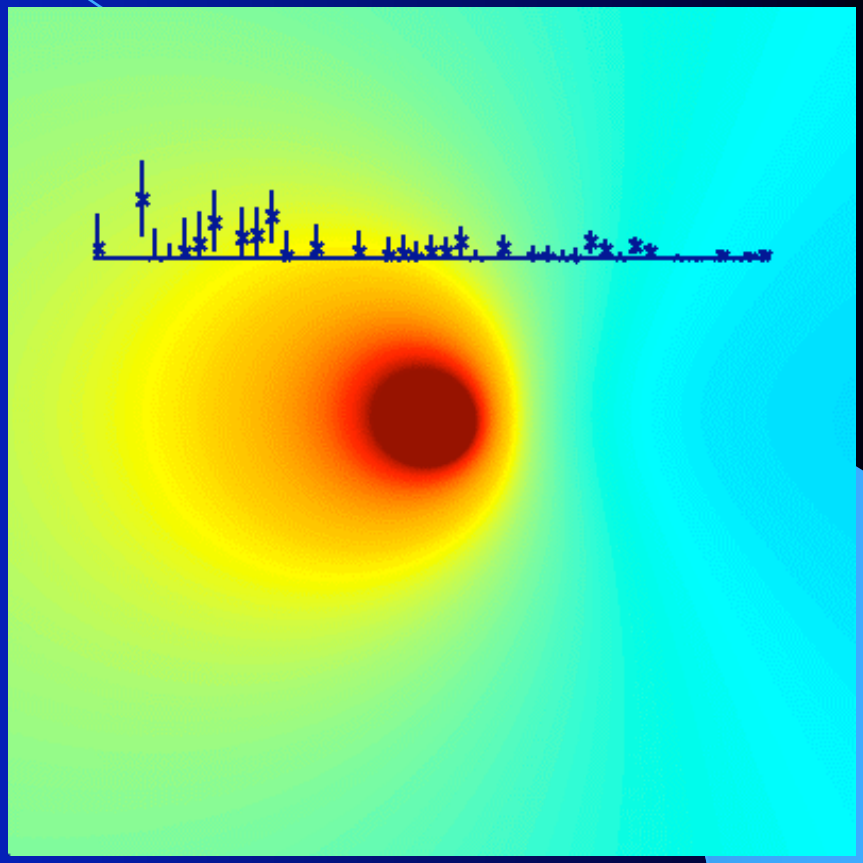
$r=3r_g$; a=0.95; $M=3\times10^7\ M_{sun}$

- Fit <u>each</u> track for (r,a) assuming Kerr metric
  - Kerr metric ⇒ a(r)=constant

Currently developing track simulations and fitting tools to judge sensitivity

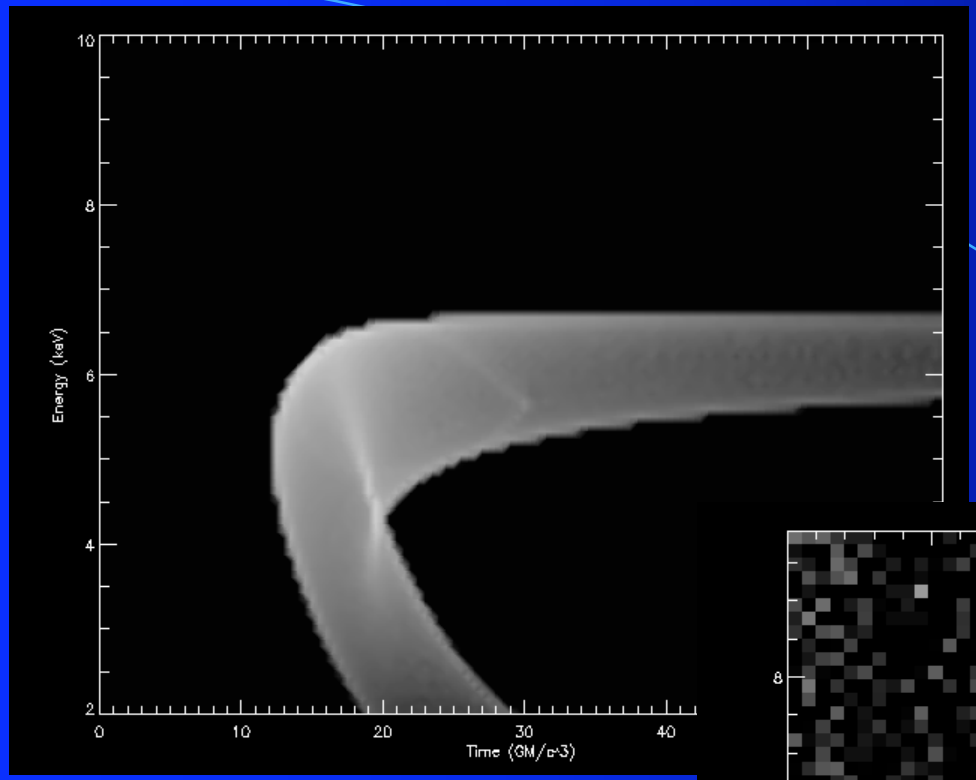
Jet or thick corona :
Iron line reverberation



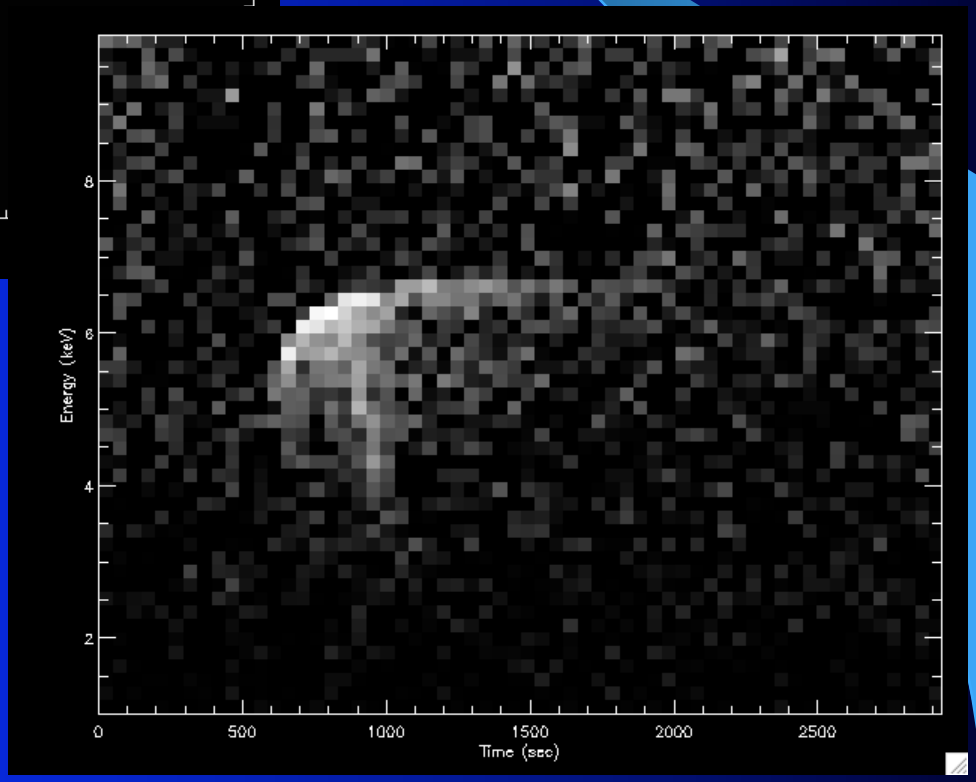


Transfer function encodes flare-position as well as geometry of space-time

Reynolds et al. (1999)
Young & Reynolds (2000)



Courtesy of Andy Young



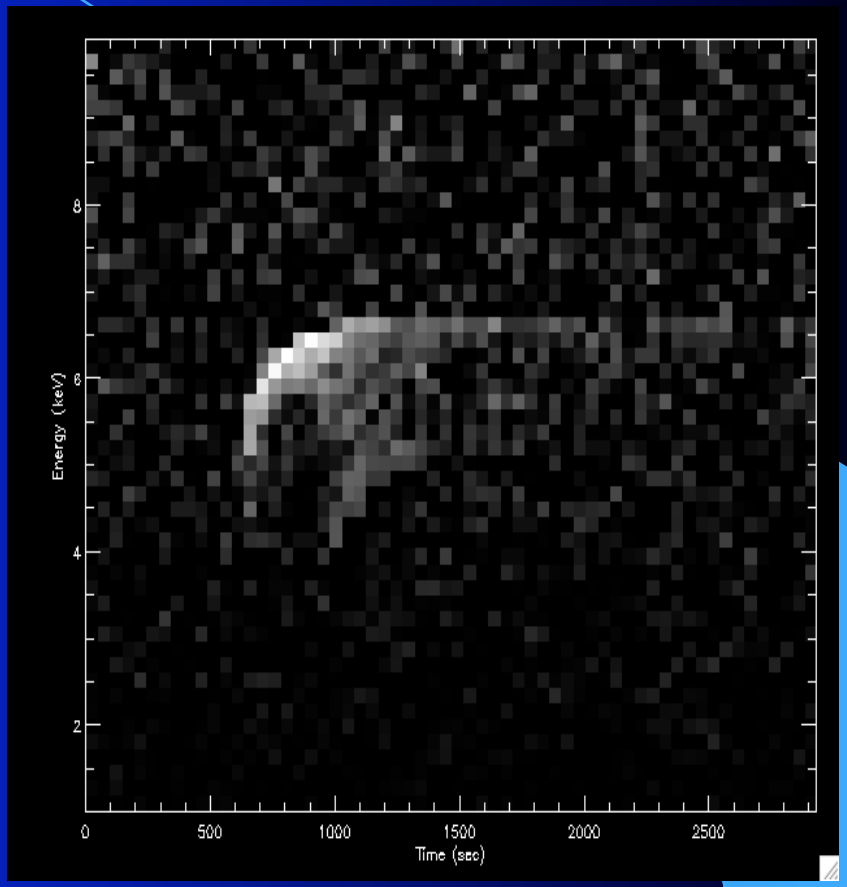
a=0.998

$M=10^7\ M_{sun}$
$F_{2\text{-}10}=5\times10^{-11}$

Developing iron line reverberation…

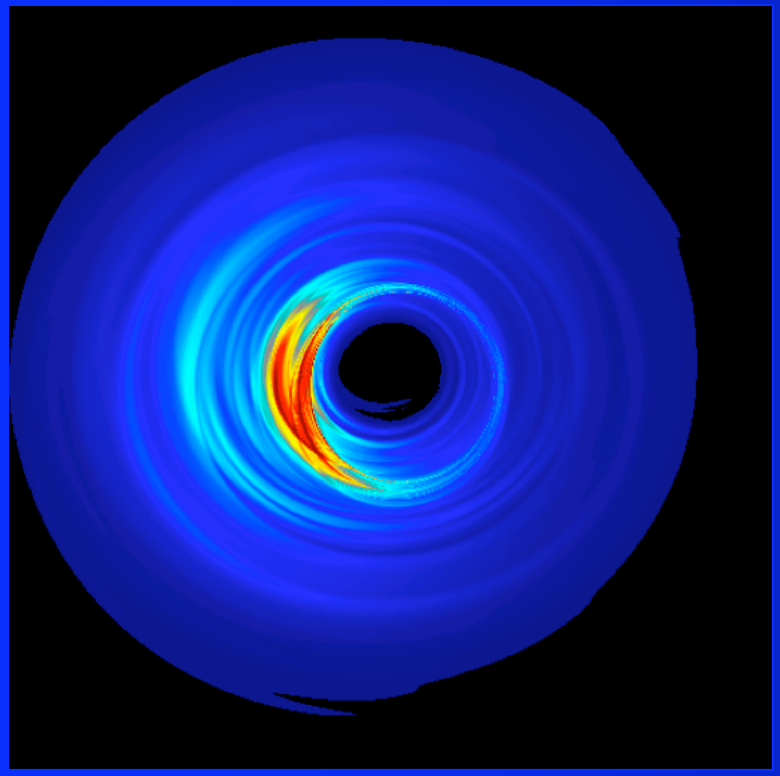
Open questions…

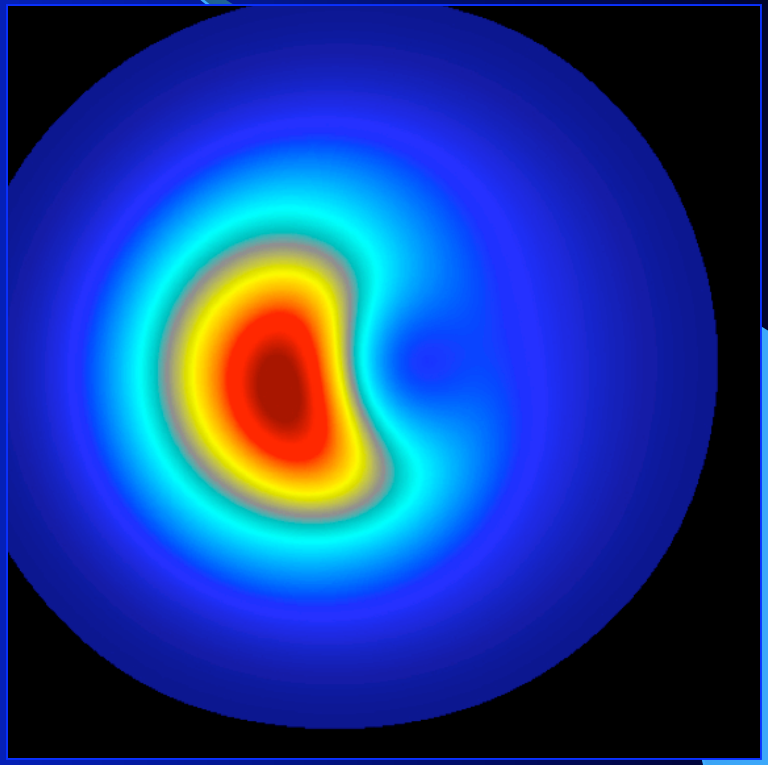
- Can effects of metric and source geometry be disentangled?
- Can we use cross-correlation techniques to effective add many TFs
- How would we really proceed with the data analysis…



"Directly comparing signatures in GR and alternative theories" is NOT a viable option… no viable alternative to GR is currently developed sufficiently to allow these calculations

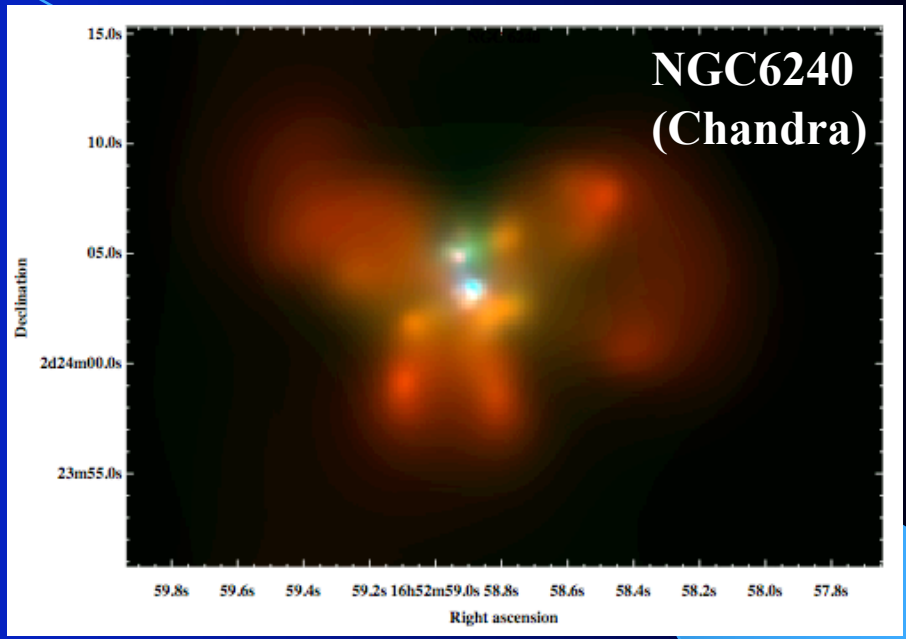
Other interesting issues…
Sgr A* and synergy with mm-VLBI

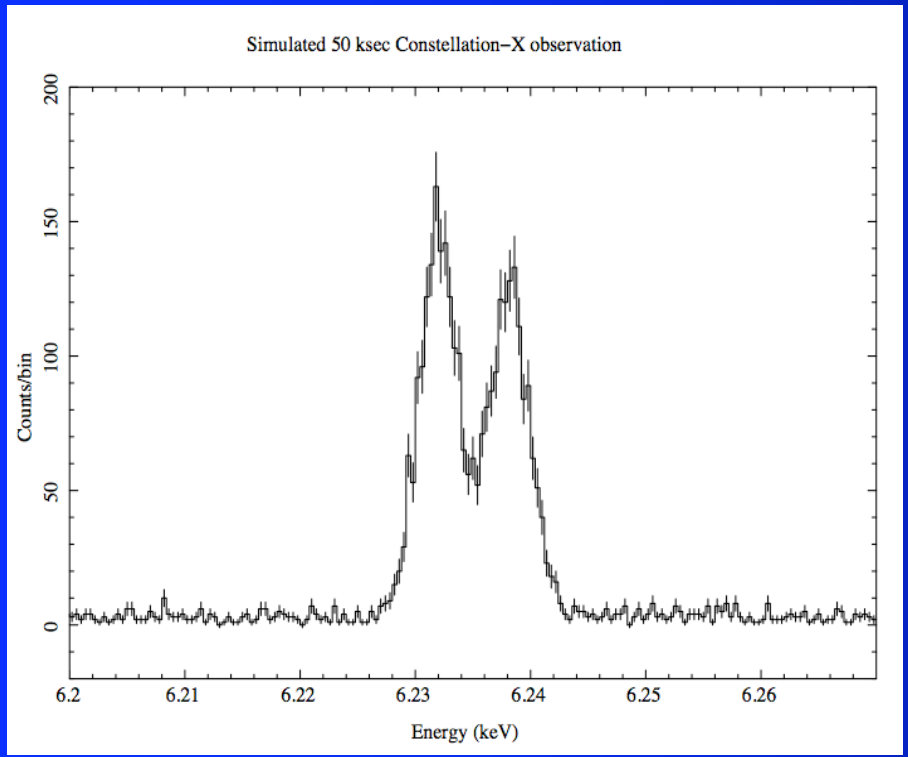




mm-VLBI will enable imaging of strong-field region in Sgr A*
Will assess utility of contemporaneous Con-X data

Binary supermassive black holes





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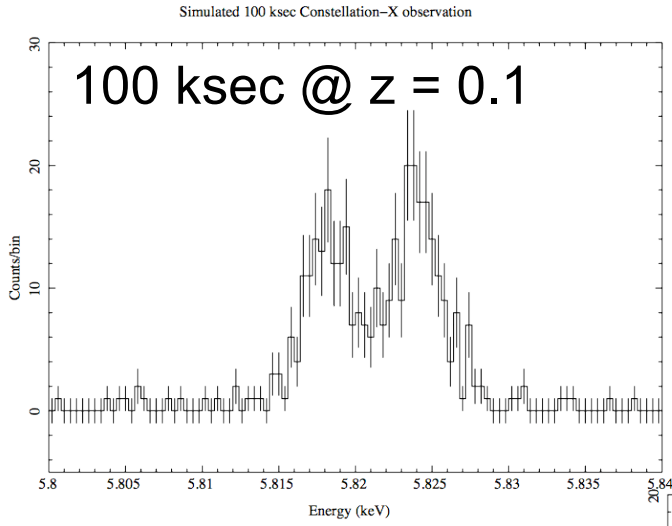
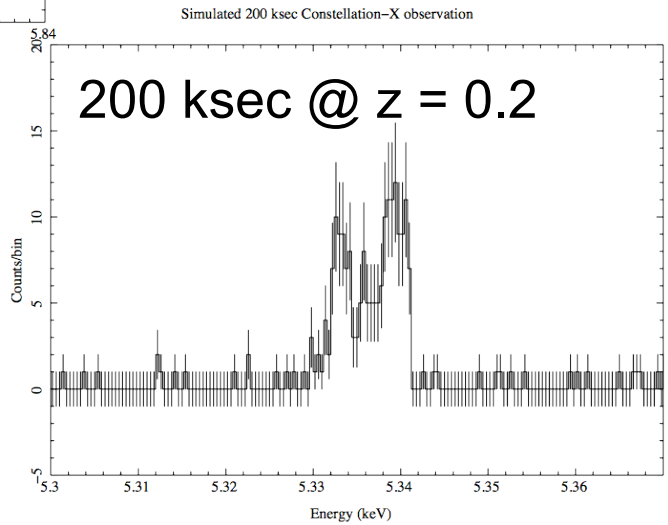
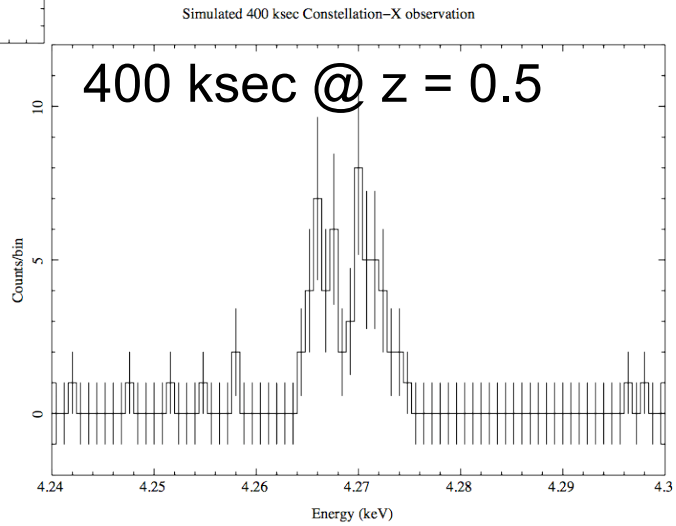


Estimate 1-10 SMBH binaries per Con-X field-of-view





Andy Young

Main conclusions

- Address our primary questions using broad iron line diagnostics…
- What are the demographics of black hole spin?
  - Building upon current-day XMM and Suzaku work
  - Aim for survey to measure 200-300 AGN spins
  - All major issues in hand
- Is GR correct in the region close to the black hole horizon?
  - Need to use time-variability of iron lines
  - Major uncertainty is the geometry of the X-ray source
  - Reverberation and hot-spot probe complementary geometries…
  - Strategy better defined in case of hot-spot variability